Additive Manufacturing –
A Regulatory Perspective

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Disclaimer

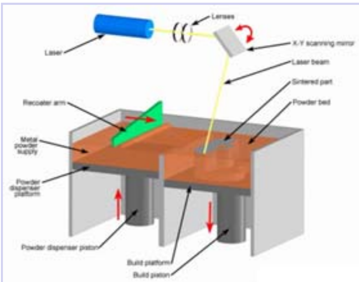
The views presented in this talk are those of the author and should not be construed as representing official Federal Aviation Administration rules interpretation or policy

What is Additive Manufacturing (AM) ?

… a *partial* list of metal AM technologies

- 3-D Printing
- Powder Bed Fusion (PBF)
- Electron Beam Melting (EBM)
- Additive Layer Manufacturing (ALM)
- Directed Energy Deposition (DED)
- Direct Metal Laser Sintering (DMLS)
- Wire + Arc AM (WAAM)
- Selective Laser Melting (SLM)
- Laser Engineered Net Shaping (LENS)
- Laser Cladding Technology (LCT)
- Laser Freeform Manufacturing Technology (LFMT)
- Laser Deposition Technology (LDT)
- Ultrasonic Additive Manufacturing (UAM)

Additive Manufacturing (AM)



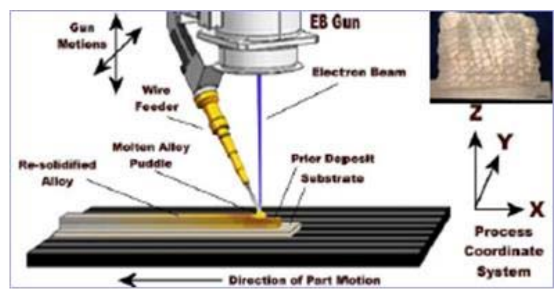
Additive Manufacturing (AM) --

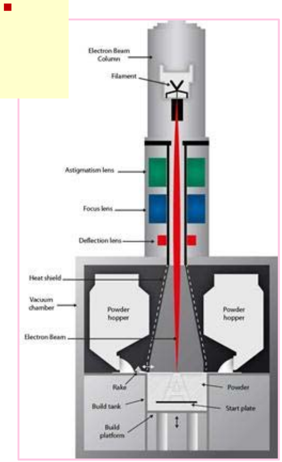
A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to *subtractive manufacturing* methodologies

(***Ref: ASTM F2792 – 12a***)

By Source of Material:
Powder vs. Wire

By Source of Energy:
Laser vs. E-Beam





What Causes Failures?

Frequency of Failure Mechanisms *)

Failure Mechanism	% Failures *(Aircraft Components)*
☆ Fatigue	55%
Corrosion	16%
Overload	14%
Stress Corrosion Cracking	7%
Wear / abrasion / erosion	6%
High temperature corrosion	2%

*) *Source: Why Aircraft Fail, S. J. Findlay and N. D. Harrison, in Materials Today, pp. 18-25, Nov. 2002.*

- **Fatigue is the Predominant Failure Mode in Service**
- **Expect this trend to continue for metallic materials**
- **Some of the most challenging requirements *for new material systems* are related to F&DT**

State of Industry - ***Today***

- **Field experience for certified metal AM parts in Civil Aviation** (*in 10,000 hours*) → **zero** ***)**
- **Full-scale production experience for metal AM parts in Civil Aviation** (*in 10,000 parts*) → **zero** ***)**

***)** **approximate as of the end of 2015 (based on information available to presenter)**

Are New "Lessons Learned" Likely..?

State of Industry (cont.)

“Additive manufacturing is the new frontier. It has taken the shackles off the engineering community, and gives them a clean canvas…”

Mr. David Joyce, GE Aviation President and CEO

"Metal parts from <u>some</u> AM systems are *already on par with their cast or wrought counterparts*. As organizations qualify and certify these and other materials and processes, the industry will grow very large…

<u>Source</u>: Wohlers Report 2012

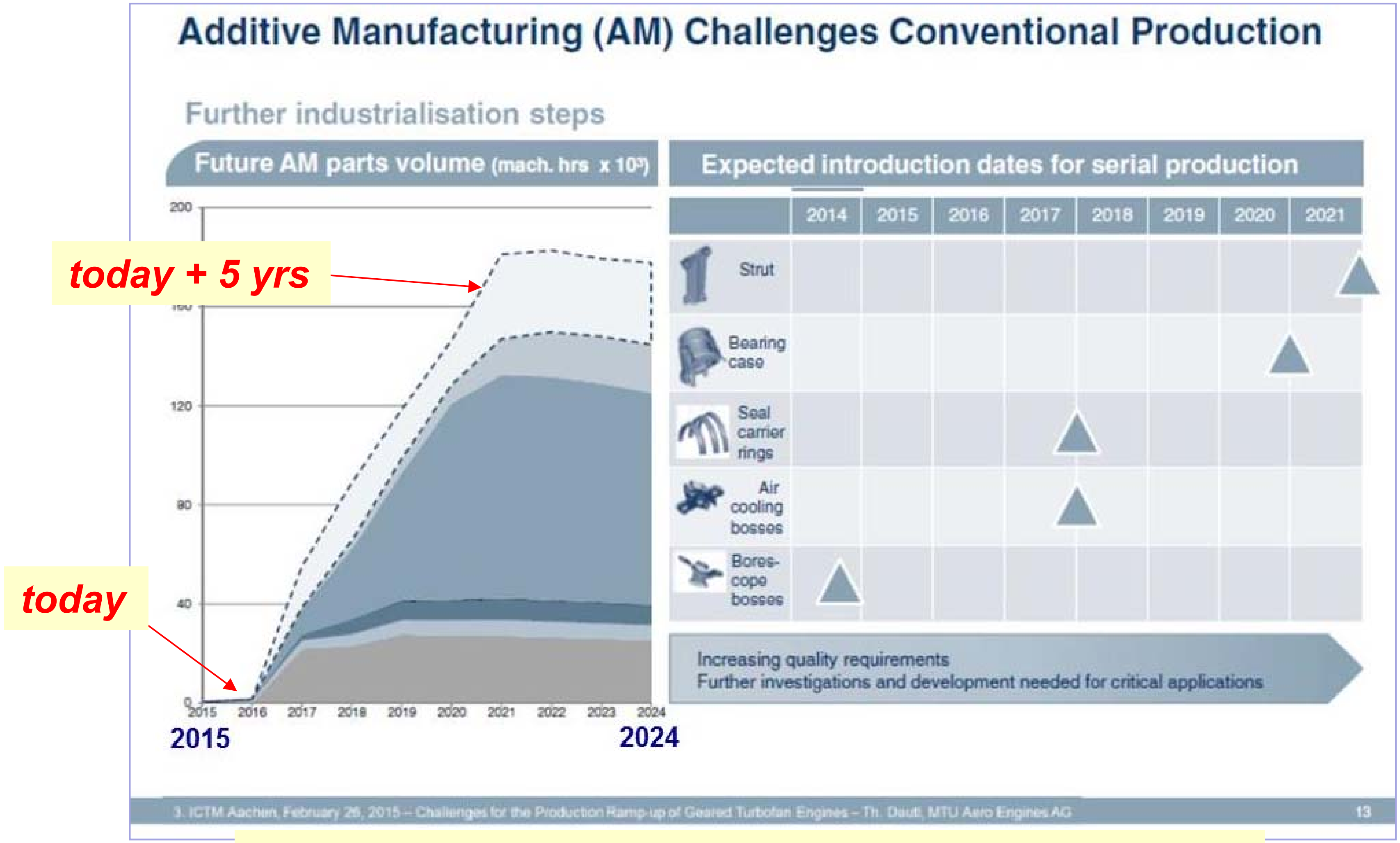
“We are on the cusp of a step-change in weight reduction and efficiency – producing aircraft parts which weight 30 to 55 %, while reducing raw material used by 90 % …”

Mr. Peter Sander, Airbus

"3D printing opens up new possibilities, new design space… Through the 3D printing process, you're not constrained [by] having to get a tool in to create a shape. You can create any shape you like.“

Dr. Henner Wapenhans, Rolls-Royce
Head of Technology Strategy

State of Industry (cont.)



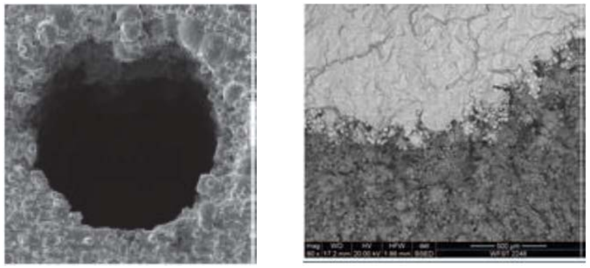
We are on the Cusp of a Significant Increase in the Use of Metal AM Parts in Commercial Aviation…

Business Drivers for AM

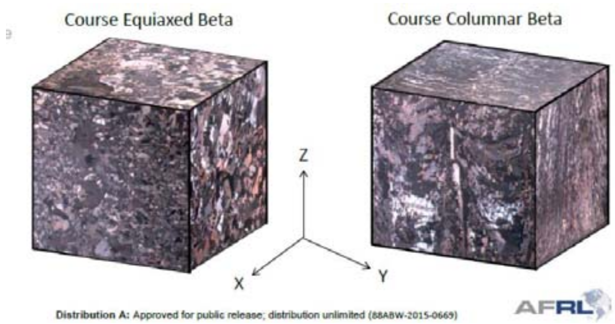
- **Part count reductions**
- **Producibility / machinability issues**
  - ***e.g. thin-wall castings***
- **More complex geometric designs**
  - ***Weight reduction***
  - ***Design optimization***
- **Single Source alternatives**
- **Production of low volume / legacy parts**
- **PMA business model (reverse engineering)**
- **Low barrier to entry for smaller businesses**

- **Business Drivers can be good *Predictors* of *Technology Trends***
- **Beware of hype – *just because something can be made using AM, doesn't mean it makes sense…***

Examples of Risk Factors for AM



Surface Quality

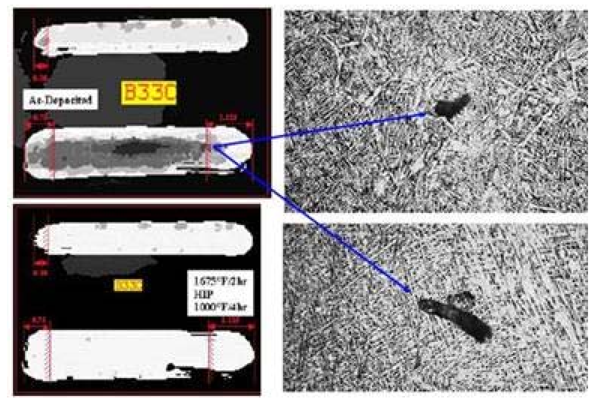


Microstructure Variability

Powder Control

Powder feed rate (g/min)	
Laser Power (W)	*over 100 process parameters identified*
Scan speed (in/min)	
Laser spot size (in)	
Substrate temp (ºF)	
Hatch spacing (% of calculated)	

Process Controls

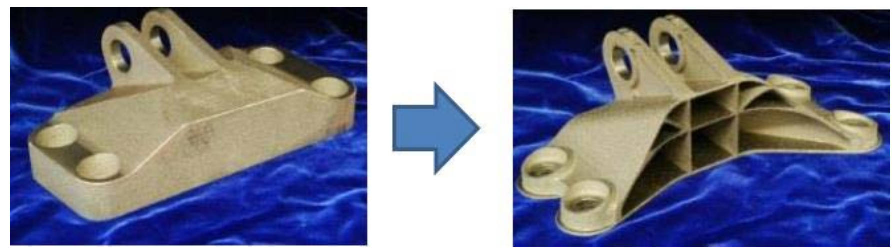


HIP Effectiveness

Many More Identified by Experts…

Topological Optimization Using AM

"*Complexity is Free…*"

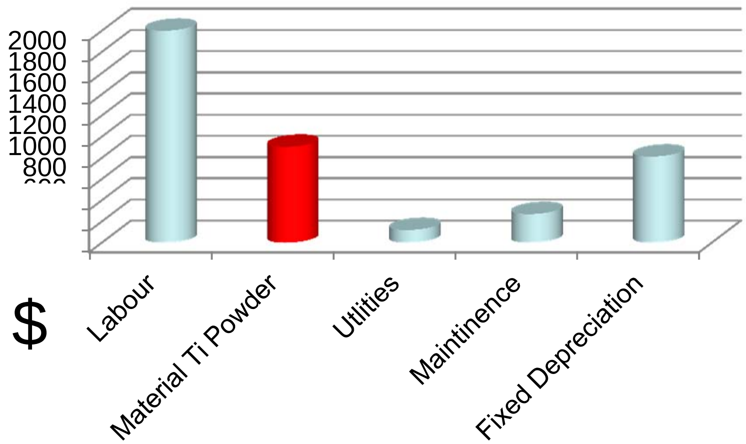


- ***… But is it really?***
  - **High number of Kt features**
  - **Inspectability challenges**
  - **Location-specific properties**
  - **Surface quality of hard-to-access areas**
    - **may need to live with as-produced surface**

Need a Realistic Assessment of Technical Challenges / Risks

Powder Reuse

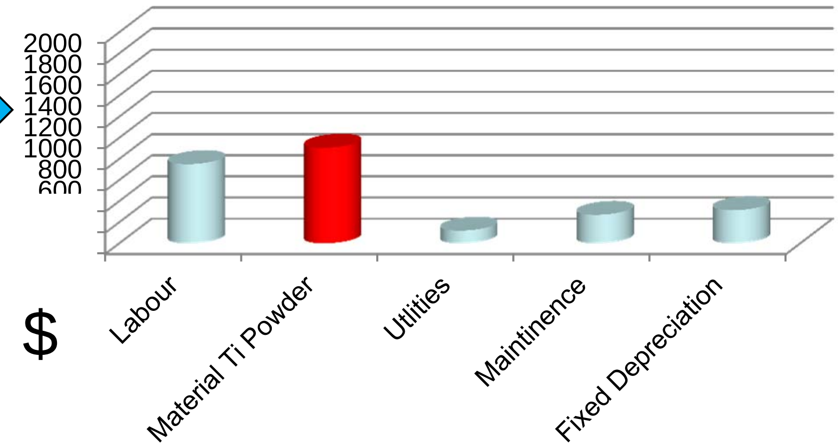
Today



50% of the cost in operation is labour

20% is depreciation (i.e. cost of the unit)

Future



As the equipment costs come down and labour gets more productive (affordable), *powder becomes the most costly component of AM*

"… it is highly likely you can reuse IN718 powder at least 14 times with no significant degradation from its initial quality…"

"… There was also no evidence of the quality degradation of final parts made with reused powder, despite *some minor changes in the powder properties relating to its particle size distribution and chemistry*."

"Printing jet engines" by James Perkins, Materials World, March 2015

AM Challenges To Be Addressed

“top five”

- **Limited understanding of acceptable ranges of variation for key manufacturing parameters**
- **Limited understanding of key failure mechanisms and material anomalies**
- **Lack of industry databases / allowables**
- **Development of capable NDI methods**
- **Lack of industry specs and standards**

Additional level of complexity – these areas are not independent…

Other considerations

- ***Lack of robust powder supply base***
- ***OEM-proprietary vs. commodity type technology path***
- ***Low barrier to entry for new (inexperienced?) suppliers***

What Did Historically Work Well to Address “Known Unknowns”?

- **Effective manufacturing process controls**
- **Damage tolerance (DT) framework**
- **QA / NDI methods**
- **Sharing of lessons learned across the industry**

Success story – rotor-grade Titanium alloys

(Reference: proceedings of AIA RISC Working Group)

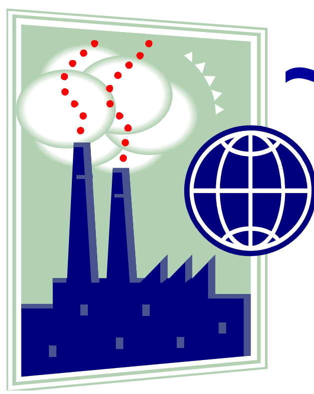
AM - "Barrier to Entry"

Optimistic →


Equipment acquisition

~ $1M

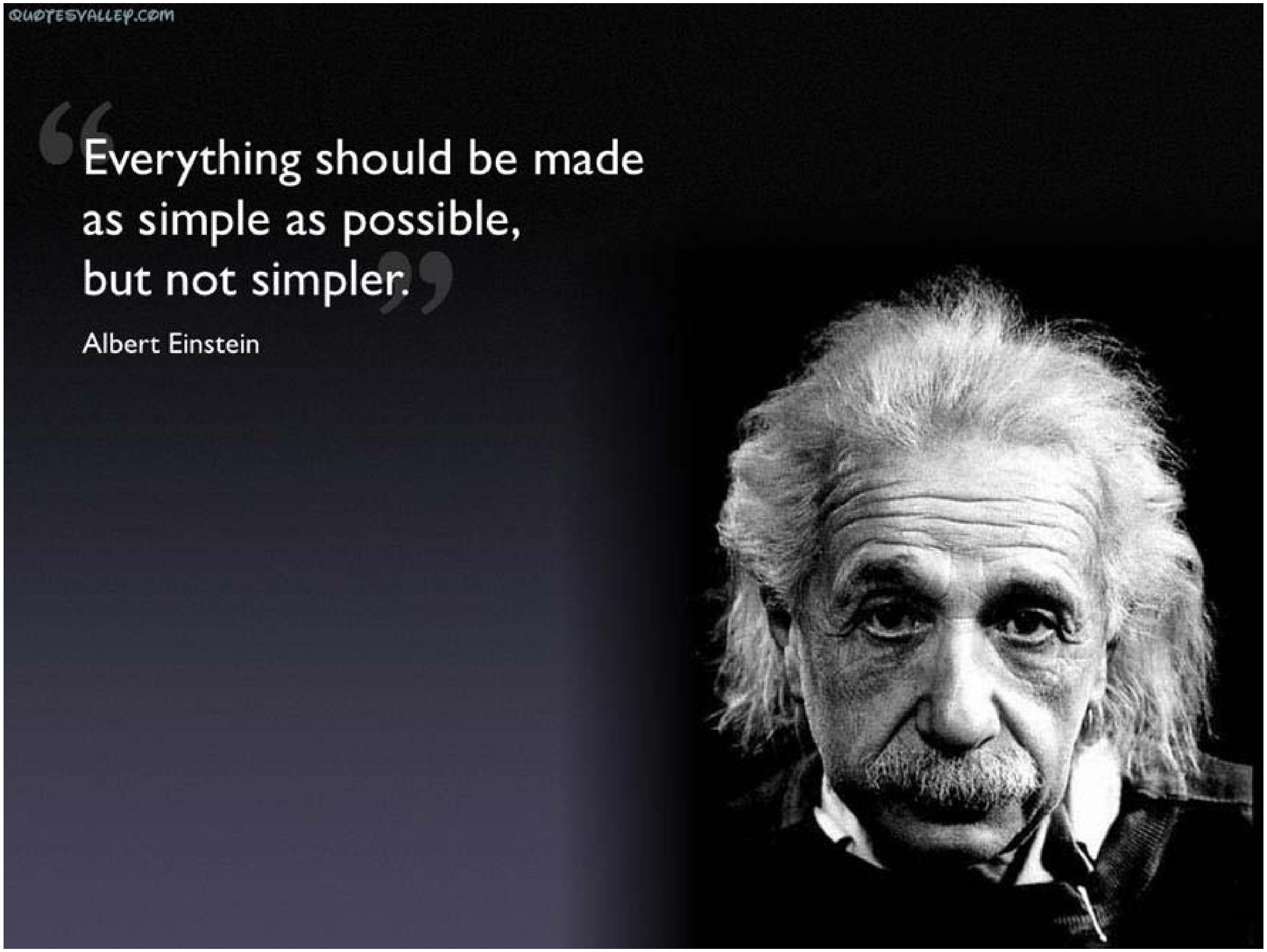
Realistic →



~ $10's of M

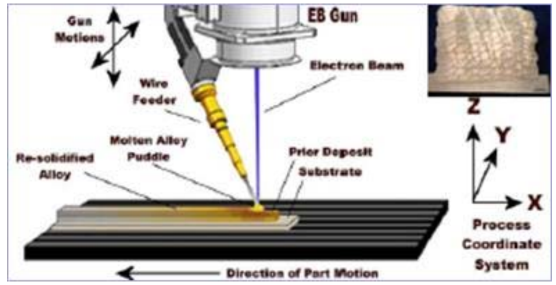
- **Process development**
- **Process qualification**
- **Process controls**
- **Material characterization**
- **Design data**
- **QA / NDI**
- **etc.**

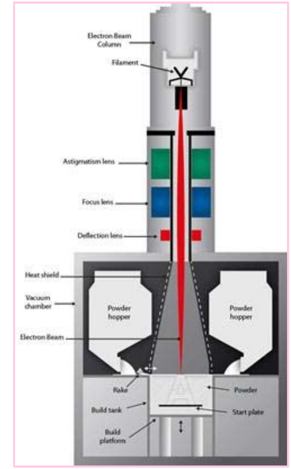
A few "regulatory" thoughts…


QUOTESVALLEY.COM
Everything should be made as simple as possible, but not simpler.
Albert Einstein

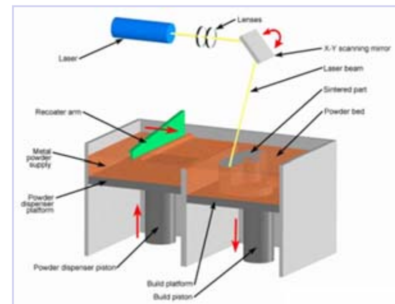
Diversity of AM Processes and Certification Domains

By Source of Material:
Powder vs. Wire





By Source of Energy:
Laser vs. E-Beam



New Type and Production Certificates	Repair and Overhaul (MROs)	Aftermarket Parts (PMAs)

Two Types of FAA Certificates for New Products *(14 CFR Part 21)*

- **Type Certificate**
  - An applicant is issued a *Type Certificate* once they have demonstrated ***through test and analysis*** that the type design data (drawings, specifications and other documents needed to describe a design) meets all relevant regulatory requirements
- **Production Certificate**
  - An applicant is issued a *Production Certificate* once their manufacturing facilities are capable of ***repeatably*** producing product *per the approved Type Certificate*

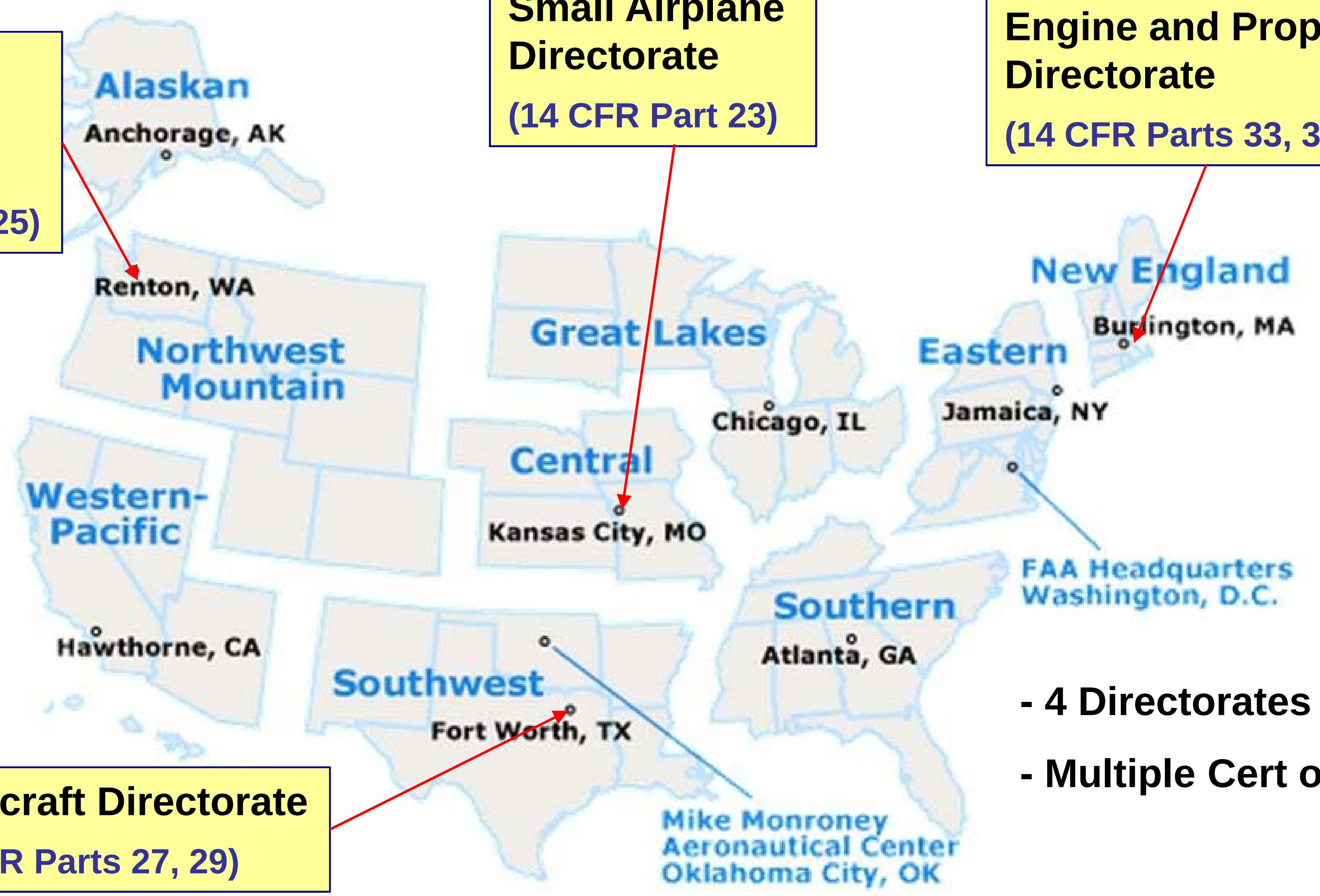
Diverse Regulatory Environment

(driven by different product types)

Transport Airplane Directorate
(14 CFR Part 25)

Small Airplane Directorate
(14 CFR Part 23)

Engine and Propeller Directorate
(14 CFR Parts 33, 35)



Rotorcraft Directorate
(14 CFR Parts 27, 29)

- 4 Directorates
- Multiple Cert office

From Non-Critical to Critical

- **Typical new aerospace alloy development and introduction timeline – *10 to 15 years***

➢ **However**

TABLE 2.2 Typical Development Times for New Materials

Development Phase	Development Time
Modification of an existing material for a noncritical component	2 to 3 years
Modification of an existing material for a critical structural components	Up to 4 years
New material within a system for which there is experience	Up to 10 years. Includes time to define the material's composition and processing parameters.
New material class	20 to 30 years. Includes time to develop design practices that fully exploit the performance of the material and establish a viable industrial base (two or more sources and a viable cost).

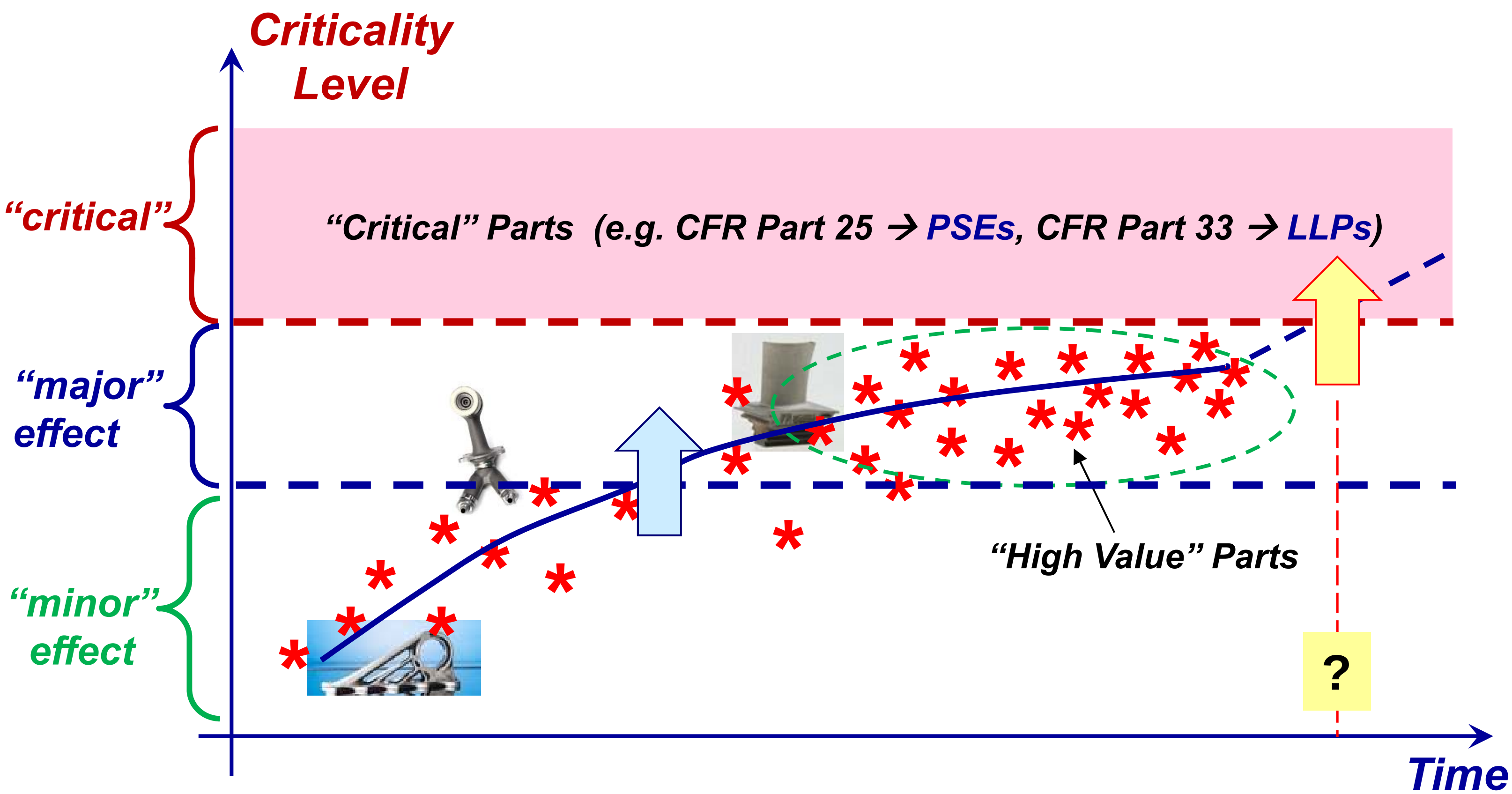
SOURCE: R Schafrik, GE Aircraft Engines, briefing presented at the National Research Council Workshop on Accelerating Technology Transition, Washington, D.C., November 24, 2003.

Example

"The *outcome* of Rawfeed (*an R&D program*) will be a *specification for a process to additively manufacture Class 1 titanium structures*, such as engine hangers, wing spars and gear ribs… expensive, critical parts…"

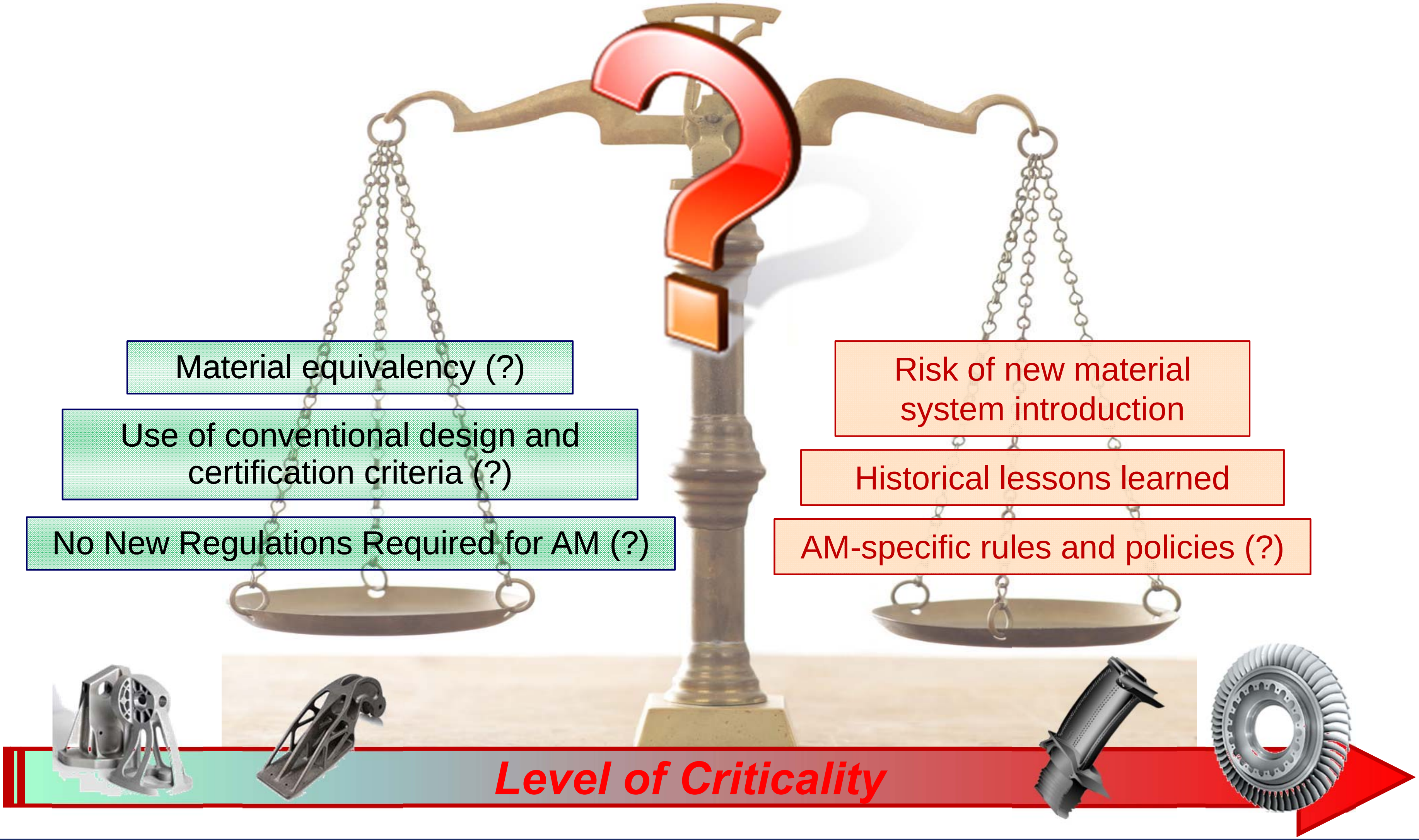
Reference: ***Rolling Key To Additive-Manufacture Of Critical Structures,* Aviation Week & Space Technology, Nov 10, 2014.**

Evolution of Criticality of AM Parts



Aggregation of parts at "sub-critical" levels may result in non-trivial *cumulative* risk impact at fleet level

Finding The Right Balance…



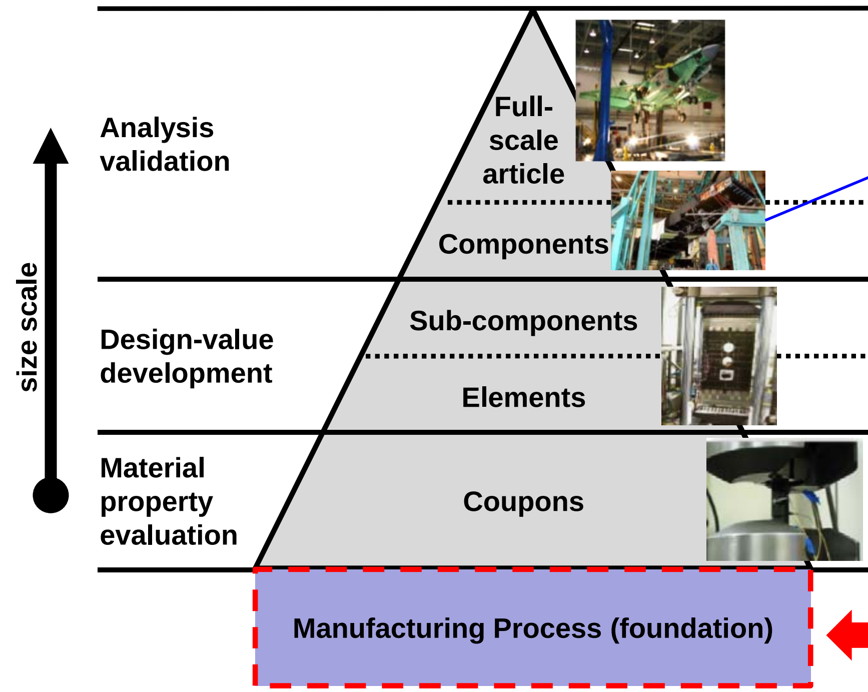
Enablers for AM Parts Certification - *Near-Term*

- **Training and education**
- **Inter-agency collaboration and exchange of Lessons Learned and R&D results**
- **Benchmarking of OEMs**
- **Focused industry working groups**
- **Certification checklists**
- **Development of interim DT criteria (..?)**

Current approach does not capture impact of ***manufacturing variability across all size scales***

Courtesy of Mr. Michael "Mick" Maher, DARPA DSO

Building Block Test Structure Required for Certification



	Specimen Count	Cost ($M)	Time (Yrs)
Full-scale article	2-3	100-125	4
Components	10-30	10-20	3
Sub-components	25-50	10-35	3
Elements	2000-5000	10-35	3
Coupons	5000-100,000	8-15	2

Effects of scale-up are not captured until the sub-component / component level testing

Redesign/Rework Iterations result in budget escalation and schedule delays

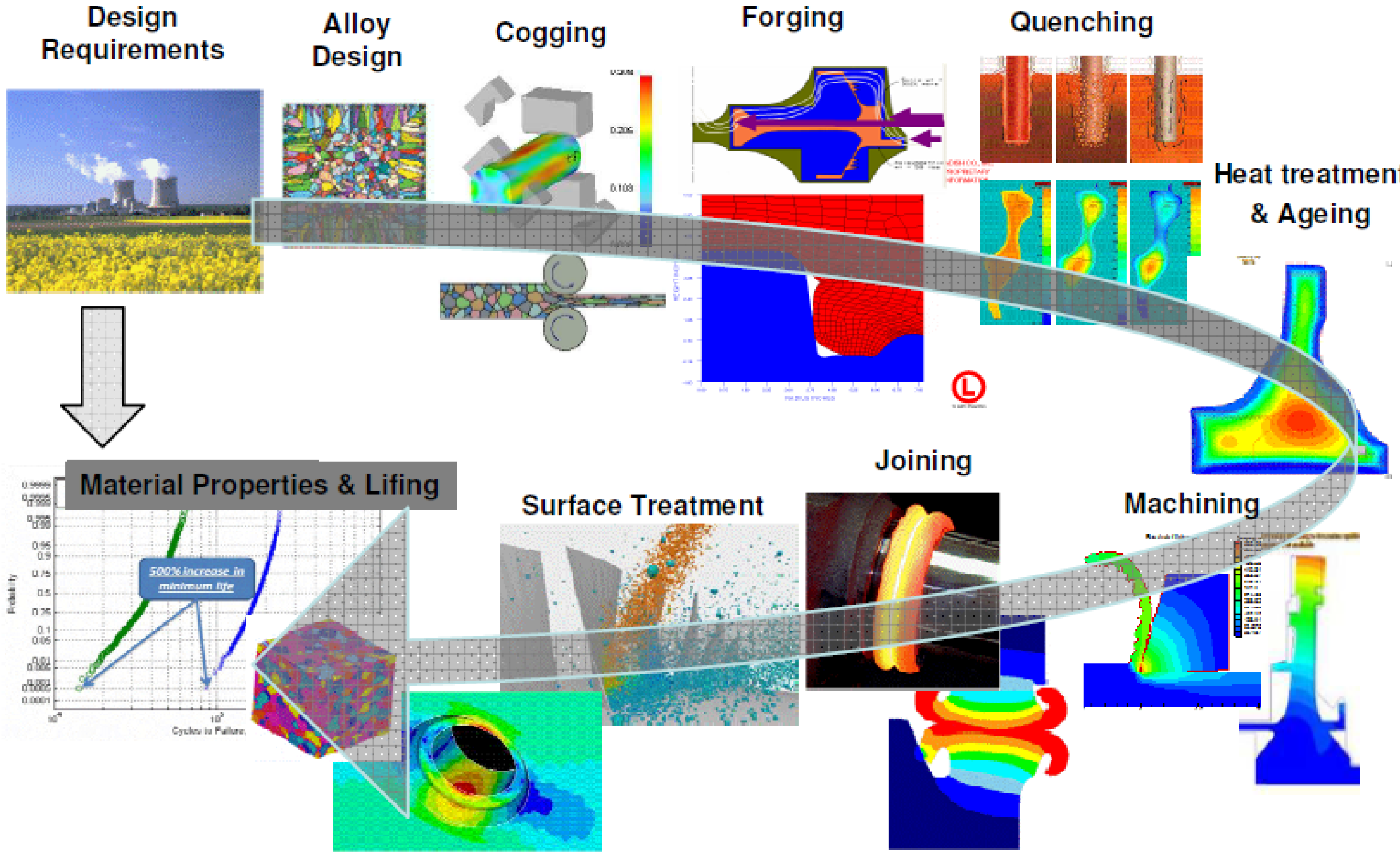
Impact: Contemporary platforms reuse traditional approaches to reduce the cost and risk of qualifying new technology

Impact of Manufacturing Parameters and Variability on material properties are never captured, understood, or controlled

Comprehensive understanding of manufacturing variation at different scales is needed

Element of a *Longer-Term* Approach – Model-enabled Qualification Framework

Example: Notional ICME Framework for Forged Components

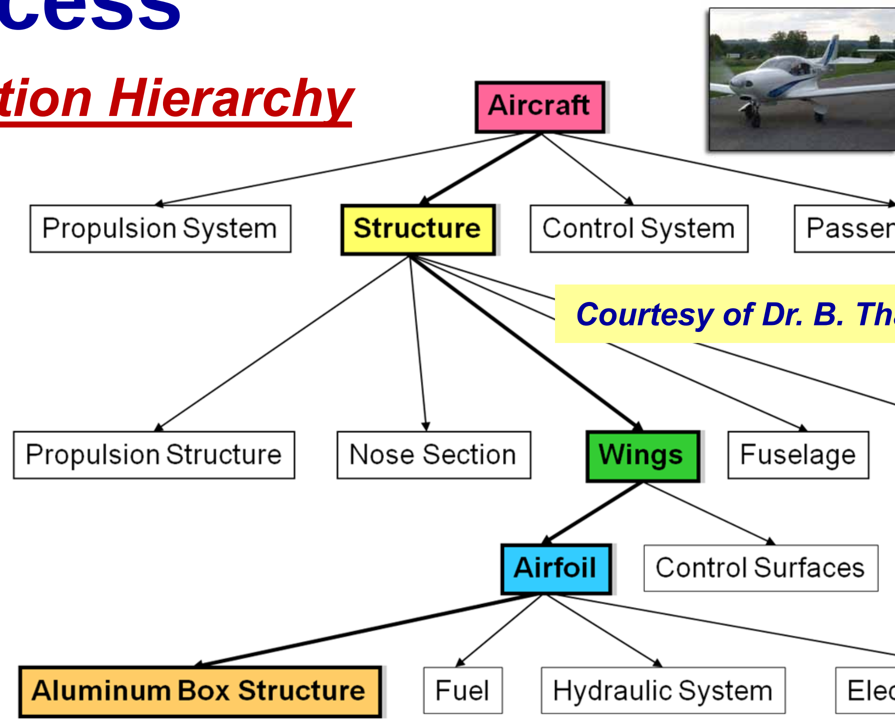


M. Glavicic et al., "Application of ICME to Turbine Engine Component Design Optimization", AIAA 2011-1738

V&V is a Key Element of the Model-Enabled Qualification Process

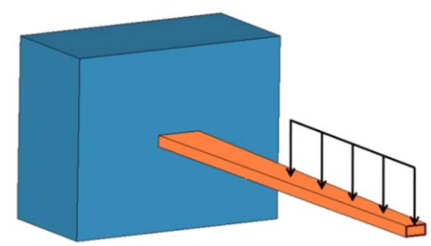
Model Development - Validation Hierarchy

- **Hierarchy is a physical and phenomenon decomposition of the top level system**
- **Use of hierarchy adds credibility: Right answer for right reason**
- **Validation team constructs hierarchy, establishes sub-level metrics and validation requirements**
- **"*Reality of Interest*" changes at each level**



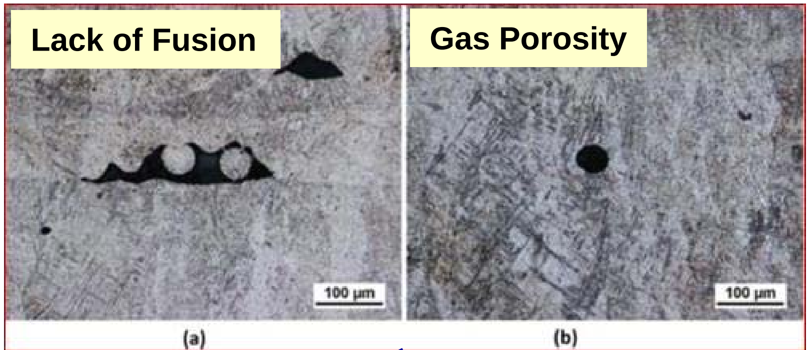
Reality of Interest

Courtesy of Dr. B. Thacker, SwRI

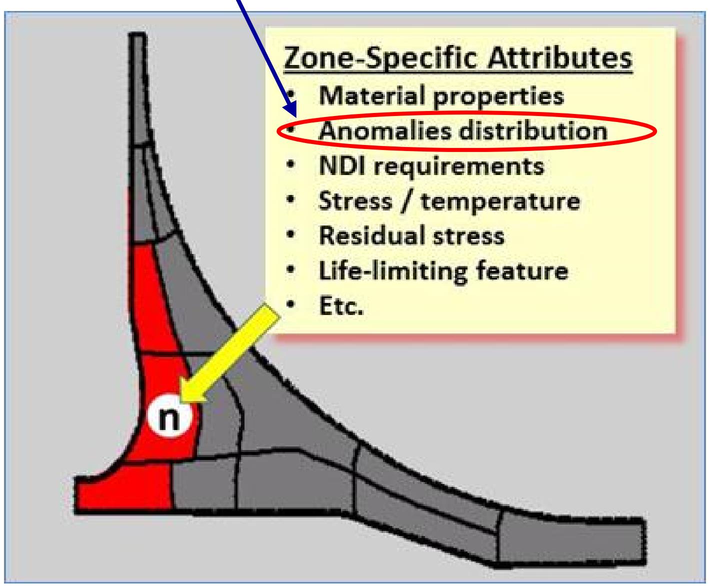


Reality of Interest

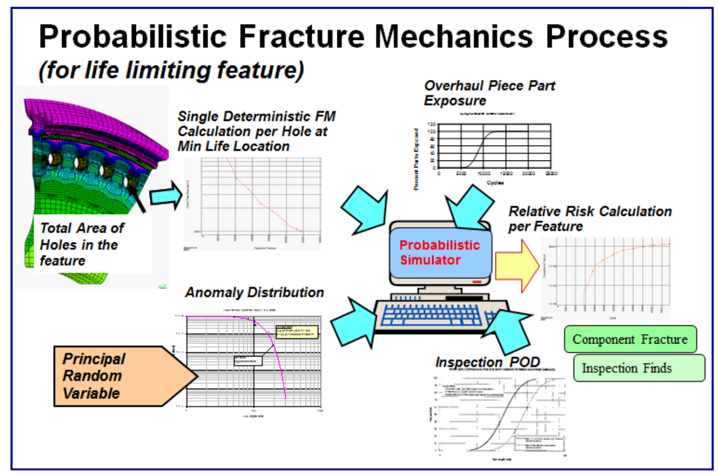
Part Zoning Considerations



- AM parts are uniquely suited for ***zone-based evaluation***
- Concept is similar to zoning considerations for castings…
- … however, modeling represents a viable alternative to empirical "casting factors"



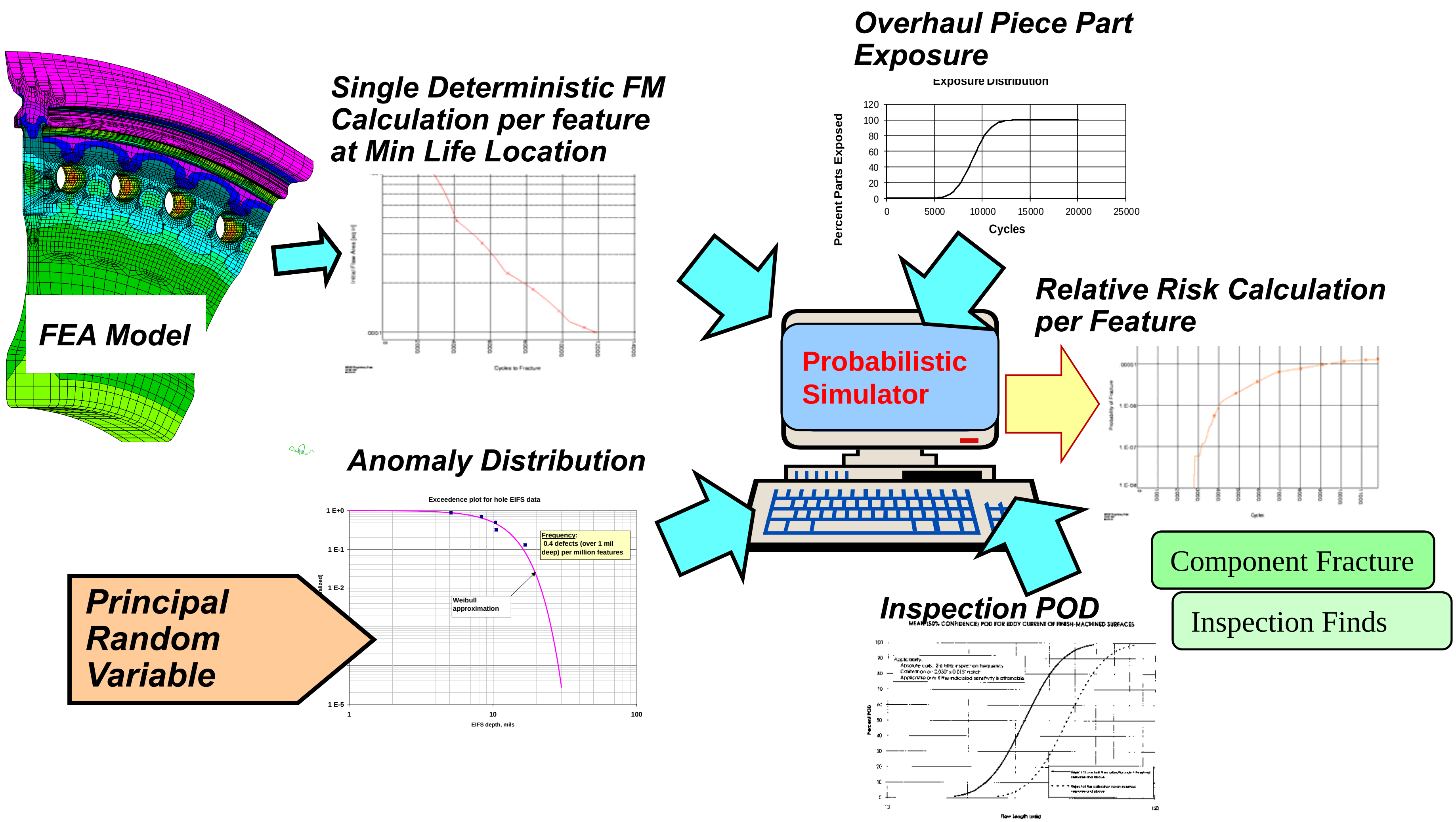
*One Assessment Option – PFM *)*



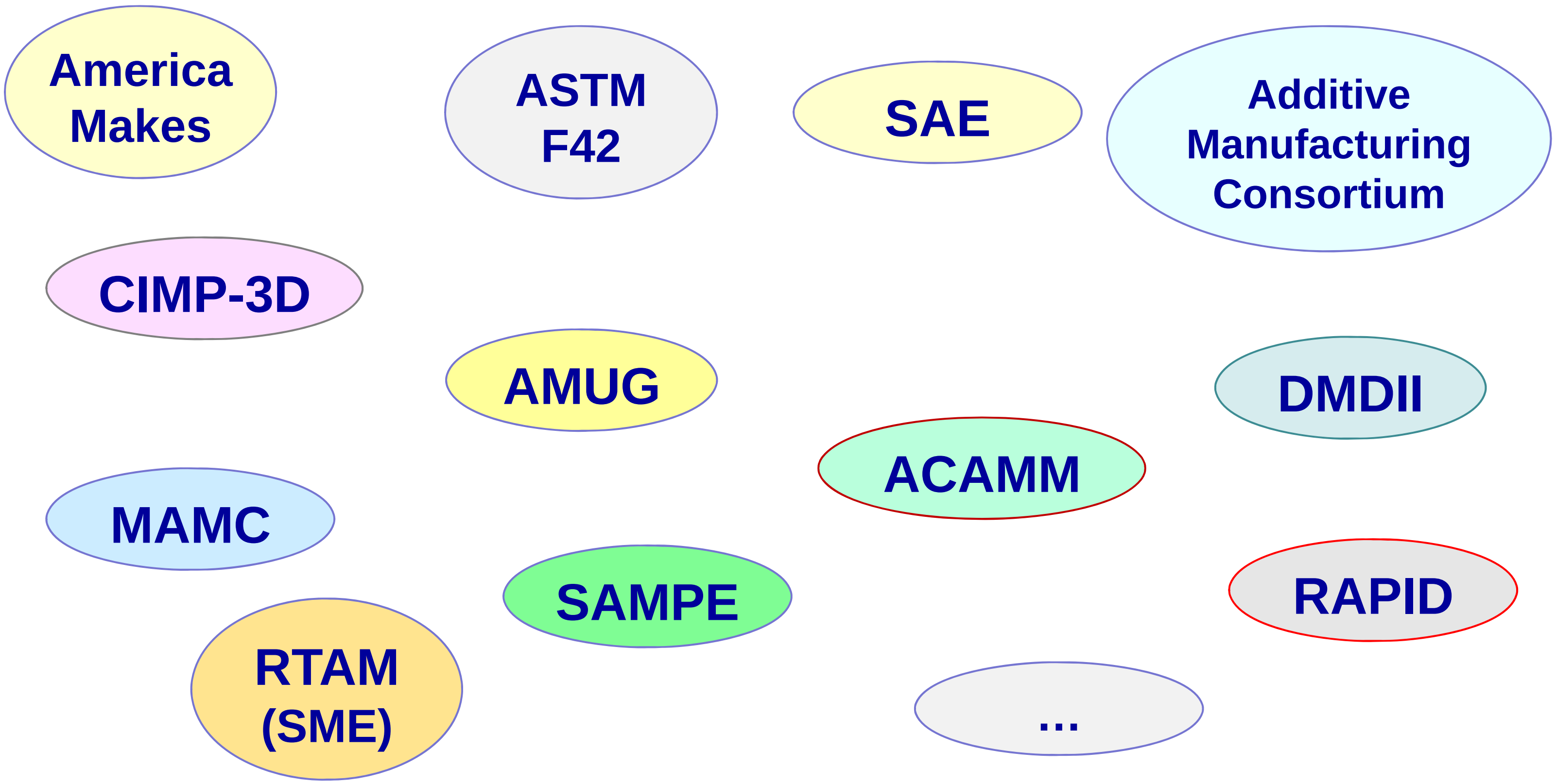
***) PFM - Probabilistic Fracture Mechanics**

(see next page)

Example: PFM Process *(for a life limiting feature)*

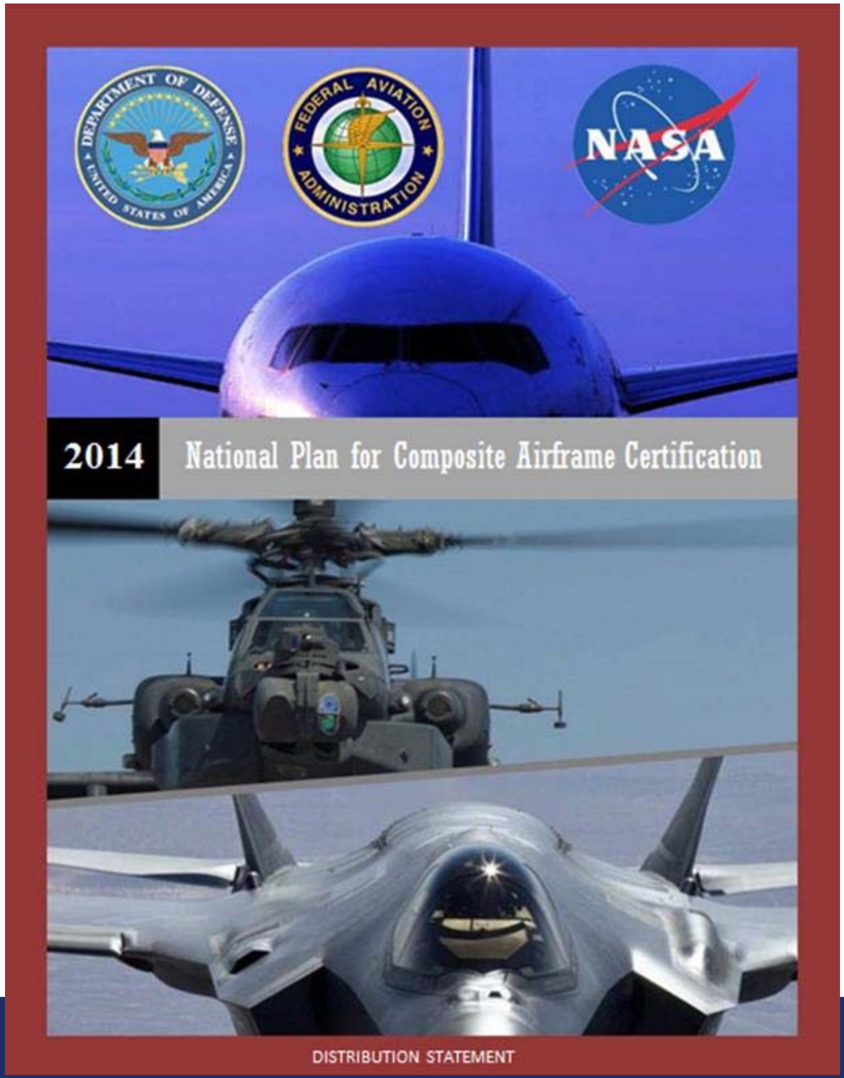


Industry and Government Collaboration on AM is Rapidly Expanding …



- *Vision of several organizations is to Develop a National Strategy for AM*
- *However … few are focused on Qual and Cert issues*

Longer-Term - Development of a National Roadmap for AM Certification (..?)



- ***Benchmarking of Composites experience***

Summary

- **Expected (rapid) expansion of AM in Aviation**
- **Expected increase in the levels of AM parts criticality**
- **Appropriate regulatory framework is a key enabler**
- **Most OEMs and agencies support *risk-based approach*, including "system-level" considerations:**
  - Manufacturing process controls and specs development
  - Identification and characterization of key failure modes and anomalies
  - Lifing system and certification criteria
  - QA, Process Monitoring and NDI methods

➢ ***Industry, agencies and societies collaboration is needed to ensure safe introduction of AM in the National Airspace***

Discussion

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